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Modulation Considerations for the Transmission of Real-Time Space Television

31 MAY 1963

Prepared by JEAN A. DEVELET, JR.
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Prepared for COMMANDER SPACE SYSTEMS DIVISION
UNITED STATES AIR FORCE
Inglewood, California

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ABSTRACT

In recent years, the field of space communications and telemetry has seen channel information capacity grow from a few kilobits to megabits per second. A principal factor for the interest in megabit channels is the increasing requirement for real-time, high-definition, television transmission. This requirement is a natural result of the existence of communication satellites which will soon continuously link the continents with a high capacity communication channel. The modulation techniques for the Telstar and Relay communication satellites were determined by considerations identical to those presented in this report. In addition, the soft landing of instruments and men on the moon makes a real-time television link with the earth during critical maneuvers highly desirable.

The question now arises as to the best method of constructing such a communication link. Recently, there has been much discussion about the type of modulation, quality, power levels, and necessary receiver sensitivities required to realize such a channel. This report briefly reviews some of the fundamentals requiring consideration before a reasonable solution at any point in the state of the art can be determined.

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I. INTRODUCTION

In recent years, the field of space communications and telemetry has seen channel information capacity grow from a few kilobits to megabits per second. A principal factor for the interest in megabit channels is the increasing requirement for real-time, high-definition, television transmission. This requirement is a natural result of the existence of communication satellites which will soon continuously link the continents with a high capacity communication channel. The modulation techniques for the Telstar and Relay communication satellites were determined by considerations identical to those presented in this report. In addition, the soft landing of instruments and men on the moon makes a real-time television link with the earth during critical maneuvers highly desirable.

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Implementation of the receiver, a key component for a wideband-band frequency modulation (WBFM) communication system, is the subject of Ref. 1.

II. DISCUSSION

A. GENERAL

To better define the problem, a 525-line video baseband signal, typical of a high definition television system, is selected for analysis. To illustrate two extremes of transmission possibility, the baseband signal is assumed (1) digitally encoded and modulated on the carrier as binary PCM/PM -- an efficient and yet simple digital modulation -- and (2) directly analogue modulated as wideband FM. The performance and complexity of these two systems is then reviewed with parameters typical of a moon mission. Brief mention is also made of the improvement to be expected by a more exotic orthogonal coding scheme for the digital implementation.

Table 1. Characteristics of Monochrome Television Signal (from Ref. 2, Courtesy of International Telecommunication Union)

Item	Description of Item	System: 405	525 [2]	625 [3]	Belgian 625	I.B.T.O. 625	819	Belgian 819
	Video characteristics							
1	Number of lines per picture (frame)	405	525	625	625	625	819	819
2	Field frequency (fields/second)	50	60	50	50	50	50	50
3	Interlace	2:1 *	2:1 *	2:1 *	2:1 *	2:1 *	2:1 *	2:1 *
4	Picture (frame) frequency (pictures/second)	25	30	25	25	25	25	25
5	Line frequency and tolerance when operated non-synchronously (lines/second)	10,125	15,750	15,625 ± 0·1%	15,625 ± 0·1%	15,625 ± 0·05%	20,475	20,475 ± 0·1%
6	Aspect ratio (width: height)	4:3 *	4:3 *	4:3 *	4:3 *	4:3 *	4:3 *	4:3 *
7	Scanning sequence (lines) (fields)	Left to right * Top to bottom *	Left to right * Top to bottom *	Left to right * Top to bottom *	Left to right * Top to bottom *	Left to right * Top to bottom *	Left to right * Top to bottom *	Left to right * Top to bottom *
8	System capable of operating independently of power supply frequency	Yes *	Yes *	Yes *	Yes *	Yes *	Yes *	Yes *
9	Approximate gamma of picture signal	0·4-0·5	0·45	0·5	0·5	0·5	0·6	0·5
10	Nominal video bandwidth (Mc/s)	3	4·2 (4·0)	5	5	6	10	5
	Radio frequency characteristics							
a	Nominal radio-frequency bandwidth (Mc/s)	5	6	7	7	8	14	7
b	Sound carrier relative to vision carrier (Mc/s)	—3·5 *	+4·5 *	+5·5 *	+5·5 *	+6·5 *	11·15	+5·5 *
c	Sound carrier relative to nearest edge of channel (Mc/s)	+0·25 *	—0·25 *	—0·25 *	—0·25 *	—0·25 *	0·02	—0·25 *
d	Nominal width of main sideband (Mc/s)	3	4·2 (4)	5	5	6	10	5
e	Nominal width of vestigial sideband (Mc/s)	0·75	0·75	0·75	0·75	0·75	2	0·75
f	Type of polarity of vision modulation	A5 * positive Asymmetric sideband *	A5 * negative Asymmetric sideband *	A5 * negative Asymmetric sideband *	A5 * positive Asymmetric sideband *	A5 * negative Asymmetric sideband *	A5 * positive Asymmetric sideband *	A5 * positive Asymmetric sideband *
g	Synchronizing level as percentage peak carrier	< 3	100	100	< 3	100	< 3	< 3
h	Blanking level as percentage peak carrier	30	75	72·5-77·5 (75)	22·5-27·5	75	30	22·5-27·5
i	Difference between black level and blanking level as percentage peak carrier	5	2·875-6·75 (0)	3-6·5	3-6 (4)	3-5	5	3-6 (4)
j	Peak white level as percentage peak carrier	100	≤ 15	10-12·5 (10-15)	100	10	100	100
k	Type of sound modulation	A3	F3 ± 25 kc/s 75 µs pre-emphasis	F3 ± 50 kc/s 50 µs pre-emphasis	A3 50 µs pre-emphasis	F3 ± 50 kc/s 50 µs pre-emphasis	A3 No pre-emphasis	A3 50 µs pre-emphasis
l	Ratio vision to sound effective radiated powers (1)	4:1	2:1-1·43:1 (20:3-20:7)	5:1	4:1 (4)	2:1-5:1	4:1	4:1 (4)

* These characteristics are in accordance with Recommendation No. 212.

(1) The value to be considered are respectively the r.m.s. value of the carrier at the peak of the modulation envelope for the vision signal and the r.m.s. value of the unmodulated carrier for amplitude-modulated and frequency-modulated sound transmissions.

(2) Figures in brackets refer to Japanese 525-line system.

(3) Figures in brackets refer to Australian 625-line system.

(4) Tentative data.

B. BASEBAND SIGNAL

The exact definition of the standard 525-line television signal is in documentation issued by the International Radio Consultative Committee (CCIR), Ref. 2. In Table 1, certain physical parameters of the signal are displayed. A typical time waveform is shown in Fig. 1.

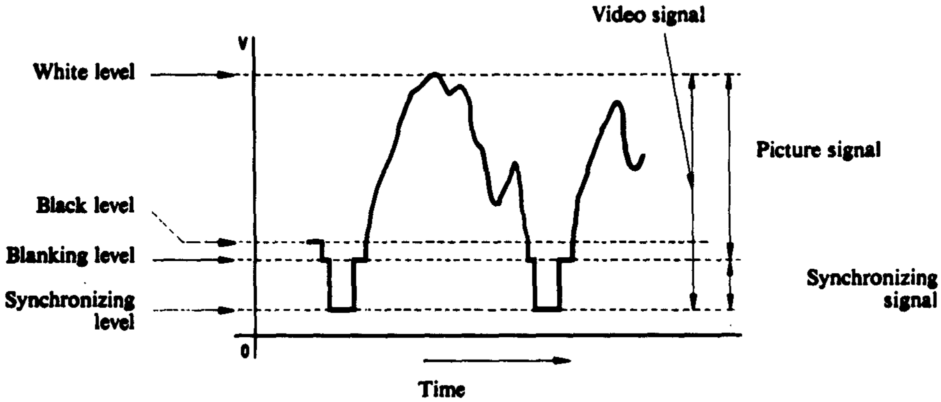


Fig. 1. Typical Television Waveforms

For purposes of communication system design, two significant parameters of this signal are the baseband width, 4.0 Mc in this instance, and the allowable noise, which may corrupt the picture. The CCIR's desired objective is a weighted signal-to-continuous-noise power ratio of 50 db. Weighting takes into account the subjective effect of noise at different frequencies. The CCIR recommended weighting to be applied to the interference prior to power measurement is shown in Fig. 2.

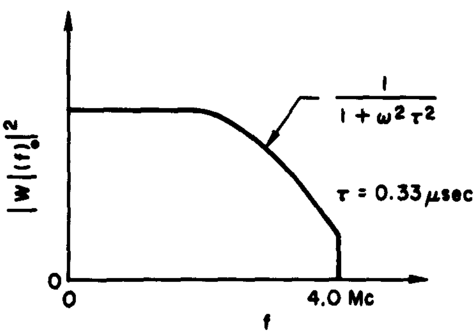


Fig. 2. CCIR Video Weighting

C. DIGITAL COMMUNICATION SYSTEM

A typical realization of television transmission by digital means appears in Fig. 3.

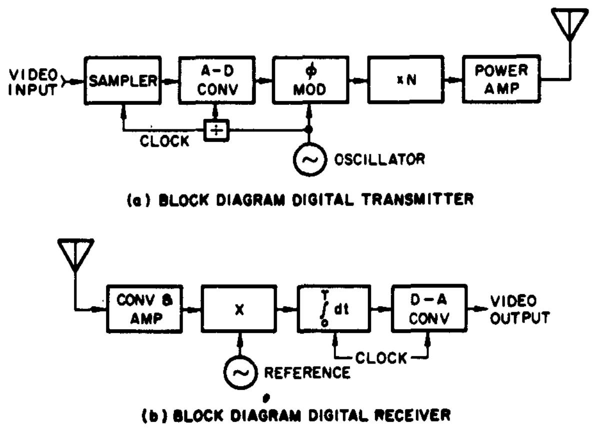


Fig. 3. Simplified Digital Communications System

The analogue video from a vidicon or other information source is converted to a binary stream at the rate of one sample every 1/2 F_{max} or 1/8 μsec. This stream is then encoded on a carrier wave in the form of phase reversals.

An object of considerable previous study has been the required number of quantum steps or levels per sample for good subjective picture quality. Bell Telephone Laboratories (Ref. 3) has concluded that 7 bits or 128 grey levels are adequate for the majority of viewers. For space television, to economize on transmitter power, a smaller number of grey levels, perhaps half as many, might be selected. For purposes of this report, 6 bits will be considered an adequate quantization. It should be noted that the subjective effect of quantization noise is not similar to that of continuous random noise; i.e., a weighting filter, similar to that described for continuous random noise, is not usually applied in treating this effect.

A qualitative picture of quantization noise, or contouring, which is characteristic of a digital picture, is shown in Fig. 4.

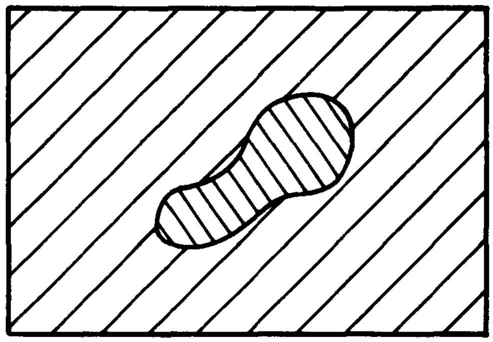


Fig. 4. Digital Television, Contouring

Since quantization has been briefly discussed, it is appropriate to examine another significant parameter in a digital communication system, viz., error rate. Assuming that out of the 6 bits per sample only the 2 significant bits can cause subjectively important errors, the tolerable error rate may be approximated as follows:

$$\begin{aligned}
\text{sec/frame} &= 1/30 \\
\text{samples/sec} &= 8 \times 10^6 \\
\text{samples/frame} &= (8 \times 10^6)/30 \\
\text{allowable errors/frame} &= 100 \\
\text{sample error rate} &= (3 \times 10^3)/(8 \times 10^6) \\
\text{significant bits/sample} &= 2 \\
\text{bit error rate} &\cong [(3 \times 10^3)/(2 \times 8 \times 10^6)] = 1.9 \times 10^{-4}
\end{aligned}$$

For simple binary PCM/PM, an error rate of 1.9×10^{-4} requires an energy per bit/noise density ratio of about 6.0. The energy per bit required by a more complex bi-orthogonal system (Ref. 4) having a similar sample error rate as the binary system but an alphabet of 64 letters is about 3.0 or 3 db less.

The results can be combined with the standard radar equation to yield a typical moon-to-earth, real-time, high-definition digital television link (Table 2).

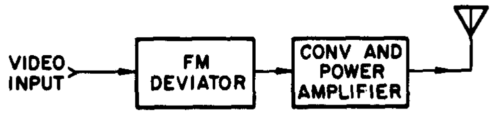
Table 2. Digital Television Moon Link

PARAMETER	VALUES	
MODULATION	PCM/PM (2L)	PCM/PM (64L)
FREQUENCY, Mc	2300	2300
TRANSMITTER POWER*, W	30	15
CABLE LOSS, db	1	1
TRANSMITTER ANTENNA GAIN (10 FT DIAM), db	34.6	34.6
SPACE LOSS (4.07×10^5 km), db	211.9	211.9
ELLIPTICITY LOSS, db	1	1
RECEIVER ANTENNA GAIN, db	52	52
RECEIVER SIGNAL POWER, dbm	−83	−86
RECEIVER NOISE DENSITY (300°K) dbm/Mc	−113.8	−113.8
RECEIVER NOISE BANDWIDTH, Mc	48	48
RECEIVER NOISE POWER, dbm	−97	−97
PREDETECTION (S/N), db	14	11
THRESHOLD, db	8	5
MARGIN, db	6	6
*EXOTIC PREMODULATION REDUNDANCY REMOVAL MAY SAVE 3 db		

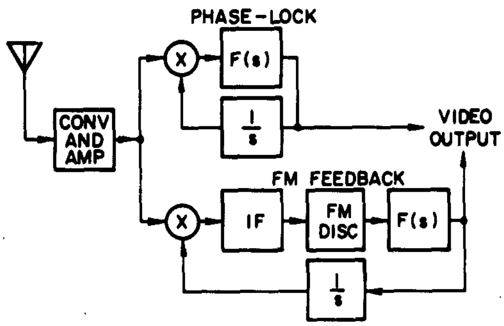
It should be noted that rather sophisticated redundancy removal, prior to modulation, will only buy about another 3 db of necessary transmitter power for a quality transmission (Ref. 5).

D. ANALOGUE COMMUNICATION SYSTEM

Realization of an analogue television link may be accomplished by the system shown in Fig. 5. The block diagram representation of the analogue system indicates it to be simpler than the digital approach, which is in fact true; the actual analogue system hardware realization is not only simpler, but it is more reliable.



(a) BLOCK DIAGRAM ANALOGUE TRANSMITTER



(b) BLOCK DIAGRAM ANALOGUE RECEIVER

Fig. 5. Simplified Analogue Communications System

The one remaining question is how the raw power requirement of the spacecraft, which uses an analogue system, compares with the power used by a digital system.

This is best answered by using very simple relationships governing the performance of modulation tracking phase-lock receivers (Refs. 6, 7). This more optimum type of receiver is essential in a space communications link, because a standard FM discriminator would require significantly more received power at threshold.

For an analogue FM system, using phase-lock reception, key relationships for quality and sensitivity are given below:

$$\frac{S_{pp}}{N_o} = 3\,\frac{S_{if}}{\Phi_{if}B_N}\cdot\left(\frac{f_{pp}}{f_m}\right)^2\cdot\frac{B_N}{f_m}\cdot W \qquad (1)$$

$$B_N = 4.03\left(\frac{f_{pp}}{\tau_r\epsilon_m}\right)^{1/2} \qquad (2)$$

$$BW_{rf} = 2f_m + f_{pp} \qquad (3)$$

$$\frac{S_{if}}{\Phi_{if}B_N} \geq 4(6\text{ db}) \qquad (4)$$

where

S_{pp}/N_o = peak-peak television output signal to noise power ratio

S_{if} = received signal power, w

Φ_{if} = receiver noise density, w/cps

B_N = receiver noise bandwidth, cps

f_{pp} = peak-peak frequency deviation, cps

f_m = highest baseband frequency, cps

W = improvement factor due to weighting (CCIR wtg, W = 12.3 db)

τ_r = 10-90 percent rise time of video waveform, sec

ϵ_m = maximum allowable phase-lock loop modulation error, rad

BW_{rf} = radio frequency bandwidth occupancy of the FM signal, cps

These relationships are valid only for a second-order receiving system with a damping of 0.707. Yovits and Jackson results, in a very significant paper in 1955, indicate that for pulse-type waveforms, such as television signals, a second-order receiver will yield minimum mean-square phase error between the received signal and the local replica. Minimizing this error yields a receiver of maximum sensitivity.

By means of parameter juggling in the undetermined set of relations shown in Eqs. (1-4),a reasonable communication link design can be achieved (Table 3).

Table 3. Analogue Television
Moon Link

PARAMETER	VALUE
QUALITY (WEIGHTED)	40 db
MODULATION	WBFM
FREQUENCY	2300 Mc
TRANSMITTER POWER	10 W
CABLE LOSS	1 db
TRANSMITTER ANTENNA GAIN (10 FT DIAM)	34.6 db
SPACE LOSS (4.07×10^5 km)	211.9 db
ELLIPTICITY LOSS	1 db
RECEIVER ANTENNA GAIN	52 db
RECEIVER SIGNAL POWER	-87.9 dbm
RECEIVER NOISE DENSITY (300°K)	-113.8 dbm/Mc
RECEIVER NOISE BANDWIDTH	24.3 Mc
RECEIVER NOISE POWER	-99.9 dbm
PREDETECTION (S/N)	12 db
THRESHOLD	6 db
MARGIN	6 db
DEVIATIONS = 10 Mc, PICTURE ONLY = 4 Mc, SYNCH RF BW = 25 Mc LOOP 3 db BW = 7.5 Mc DAMPING = 0.707	

Figure 6 shows the resulting closed-loop receiver transfer function and illustrates the wide bandwidth required for transmission of high-definition television; it should be noted that the requirements derived here have resulted in a phase-lock receiver whose bandwidth is the widest ever achieved to date. The construction of such a receiver has been accomplished but not without design problems (Ref. 1).

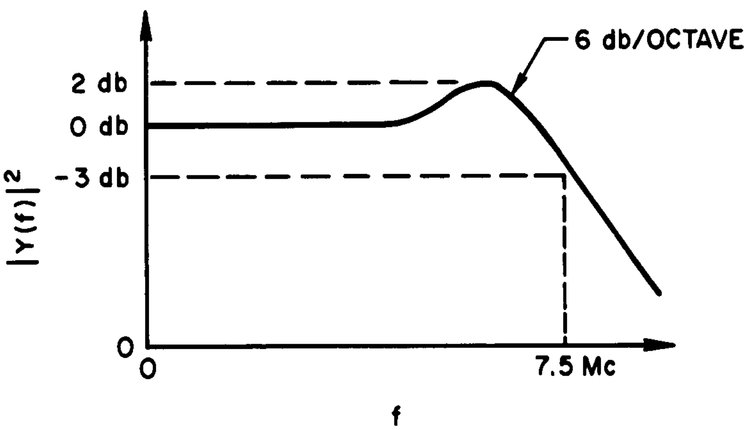


Fig. 6. Closed-Loop Baseband Transfer Function Requirement

III. CONCLUSIONS

Modulation considerations for the design of a real-time space/earth television link ~~have been~~ were treated.

To illustrate two extremes of transmission possibility, the baseband signal was assumed: (1) digitally encoded and modulated on a carrier as binary PCM/PM, and (2) analogue modulated as wideband FM.

Standards of quality established for the design of each system were then used to estimate receiver power requirements, ~~(Refs. 2-3)~~ 9 The performance and

complexity of these two approaches were then reviewed with parameters typical of a moon mission. In comparing the digital to the analogue approach, it was found that the analogue system was superior in all respects, e.g., simplicity, reliability, and spacecraft power.

Identical comparisons as the foregoing were necessary to establish the modulation techniques for Telstar and Relay, the world's first wideband communication satellites. It is not surprising, therefore, that these satellites utilize analogue wideband FM with frequency-following receivers.

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